

Dust Extinction of Gamma-ray Burst Host Galaxies: Identification of Two Classes?

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ABSTRACT

Dust in the host galaxies of gamma-ray bursts (GRBs) dims and reddens their afterglow spectra. Knowledge of the nature of this dust is crucial for correcting for extinction, providing clues to the nature of GRB progenitors, and probing the interstellar medium of high-redshift galaxies as well as the nature of cosmic dust when the universe was much younger and galaxies were much less evolved. The dust and extinction properties of GRB host galaxies are still poorly known. Unlike previous work, we derive in this *Letter* the extinction curves for 10 GRB host galaxies without a priori assumption of any specific extinction types (such as that of the Milky Way, or the Small/Large Magellanic Clouds). It is found that there appears to exist two different types of extinction curves: one is relatively flat and gray, the other displays a steeper dependence on inverse wavelength, closely resembling that of the Milky Way but with the 2175 Å feature removed.

Subject headings: dust, extinction — gamma rays: bursts

1. Introduction

The existence of dust extinction towards gamma-ray bursts (GRBs) and their afterglows has been well established *observationally* through (1) “dark bursts” – nearly $\sim 60\%$ of the X-ray afterglows have no optical counterparts – the undetected optical afterglows may have been extinguished by dust in the host galaxy (see Lazzati et al. 2002 and references therein); (2) reddening – the optical/near-infrared (IR) spectral energy distributions (SEDs) of afterglows deviate from that expected from standard models,¹ indicative of dust reddening (see Kann

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¹As any host-galaxy extinction would result in a steepening of the intrinsic spectral slope, a steeper (observed) slope (than all intrinsic spectral slopes) betrays the presence of host galaxy dust.

et al. 2006 and references therein); (3) the reduced Balmer line ratios (as a consequence of dust extinction) in the spectra of some GRB host galaxies (e.g. see Djorgovski et al. 1998) compared with the expected ratios for the standard Case B recombination (Osterbrock & Ferland 2006); (4) the depletion of dust-forming heavy elements such as Si and Fe in some host galaxies (e.g. see Savaglio et al. 2003); and *theoretically* (5) through the association of (at least long-duration $\gtrsim 2$ s) GRBs with massive stars and star-forming regions embedded in dense clouds of dust and gas (Paczynski 1998).

A precise knowledge of the nature (e.g. size, composition) of the dust in GRB host galaxies is very useful for (1) correcting for the extinction of afterglows from X-ray to near-IR wavelengths; (2) constraining the nature of the GRB progenitors (i.e. collapsing massive stars or merging neutron binaries); and (3) understanding the interstellar medium (ISM) of high-redshift galaxies and the cosmic star formation history (e.g. see Ramirez-Ruiz et al. 2002).

However, our knowledge of the dust in GRB host galaxies is very limited. Previous studies all are limited to a qualitative and rather speculative analysis of the extinction curves derived by fitting the observed optical/near-IR SEDs of GRB afterglows with a power-law (approximating their intrinsic spectra) reddened by an extinction law of known types (mostly either that of the Milky Way [MW], the Small Magellanic Cloud [SMC], or that of the Large Magellanic Cloud [LMC]) adopted as a priori (e.g. see Stratta et al. 2004, Kann et al. 2006).

In this *Letter*, by assuming that the GRB afterglows have a power-law intrinsic spectrum as expected from the standard fireball model, we obtain the extinction curves for 10 GRB host galaxies without a priori assumption of the extinction law. The size and composition of the dust are modeled quantitatively in terms of the silicate-graphite interstellar grain model.

2. Method

In the standard fireball model, the temporal (t) and frequency (ν) dependence of GRB afterglows can be well described by $F_\nu(t) \propto t^{-\alpha} \nu^{-\beta}$, where both α and β are related with the electron energy distribution index p ($dn \propto E^{-p} dE$ for the energy distribution of the shock-heated electrons; see Sari et al. 1998). Therefore, with the decay index α determined, p as well as the intrinsic spectral index β can be well constrained.

In addition to the extinction of the host galaxy, GRB afterglows are also subject to the extinction of our own MW galaxy. We correct for the latter using the reddening maps of Schlegel et al. (1998). The host’s spectrum is redshifted to longer wavelengths where any errors in the Schlegel et al. map are not important.

Let F_λ^0 be the intrinsic spectrum. With the Galactic reddening corrected, the observed wavelength (λ)-dependent spectrum is $F_\lambda = F_\lambda^0 \exp(-A_\lambda)$, where A_λ is the extinction from the host galaxy. Setting V band as the zero point, we obtain $F_\lambda/F_V = (\lambda_V/\lambda)^{2-\beta_0} \exp(A_V - A_\lambda)$, where λ and $\lambda_V \equiv 5500 \text{ \AA}$ are both measured in the rest frame. With β_0 estimated from the decay index α , we can obtain $A_\lambda - A_V$ from F_λ/F_V . To determine A_V , we fit a simple function $A_\lambda - A_V = a/[1 + (\lambda/\lambda_B)^2] + b$ for $\lambda > \lambda_V$ and then extrapolate this function to $\lambda \rightarrow \infty$ to get $A_V (= -b)$ since $A_\lambda \rightarrow 0$ as $\lambda \rightarrow \infty$.

The standard silicate-graphite interstellar dust model, consisting of a mixture of spherical silicate and graphite grains, is shown successful in reproducing the extinction and IR emission of the MW galaxy, SMC and LMC (Weingartner & Draine 2001; Li & Draine 2001, 2002). We will apply this grain-mixture to model the extinction curves A_λ/A_V determined for the GRB host galaxies, but with a *simpler* functional formula for the dust size distribution: $dn \sim a^{-\eta} \exp(-a/a_c) da$ for both grain types, where a is the grain radius, ranging from 0.05 to $2.5 \mu\text{m}$, η is the power-law index, a_c is the cut-off size, and dn is the number of grains in the size interval $[a, a + da]$. The mass fraction of graphite dust is f_{gra} [for silicates it is $(1 - f_{\text{gra}})$]. In Figure 1 we show that the MW, SMC and LMC extinction curves are well fit by the silicate-graphite model with this simple dust size distribution function.

3. Data

To construct an extinction curve, one requires simultaneous multi-band photometry. We carefully collected such data from literature for ten bursts taken when their decays were in a steady power-law state (e.g. see Panaitescu & Kumar 2001, Fan & Piran 2006 for very detailed analysis). The optical and near-IR UBVRIJHK fluxes F_ν of these bursts are tabulated in Table 1. Also tabulated is β_0 , the intrinsic spectrum index calculated from fitting the decay index based on the standard model of afterglow (see §2).

To compare the extinction properties in the rest frame of each burst, in the observer frame we need to calculate $A_\lambda - A_{[V(1+z)]}$. The results are shown in Table 2. We correct the wavelength with a factor $(1 + z)$ to get $A_\lambda - A_V$ in the rest frame. Also shown in Table 2 are A_V , obtained by extrapolating $A_\lambda - A_V$ to $\lambda \rightarrow \infty$ (see §2).

4. Extinction Curves: Two Different Types?

The extinction curves (normalized to the V band) derived for these 10 host galaxies are shown in Figures 2 and 3. A common feature for these curves is the absence of the 2175 \AA

bump, which is the strongest absorption band in the MW extinction (Li 2005). They appear to fall into two categories: one is relatively gray, showing a much flatter increase with inverse wavelength λ^{-1} (we call it “Type-I”; see Fig. 2), the other displays a much steeper, almost linear increase with λ^{-1} (we call it “Type-II”; see Fig. 3).

In view of its possible practical use (e.g. in correcting for extinction of afterglows), following Fitzpatrick & Massa (1990), we take an analytical fit to these 2 extinction types:

$$A_\lambda/A_V = \begin{cases} c_1 + c_2 x + c_3 D(x; \gamma, x_0) + c_4 F(x), & x \geq 1 \mu\text{m}^{-1}, \\ k x^{1.84}, & x < 1 \mu\text{m}^{-1}, \end{cases} \quad (1)$$

where $x \equiv \lambda^{-1}$, $D(x; \gamma, x_0) = x^2 / [(x^2 - x_0^2)^2 + x^2 \gamma^2]$, and

$$F(x) = \begin{cases} 0.5392 (x - 5.9)^2 + 0.05644 (x - 5.9)^3, & x \geq 5.9 \mu\text{m}^{-1}, \\ 0, & x < 5.9 \mu\text{m}^{-1}. \end{cases} \quad (2)$$

In this fit, c_1 and c_2 determine a linear “background” term; c_3 determines the strength of the 2175 Å feature which is represented by the “Drude profile” term $D(x; \gamma, x_0)$ – the theoretical profile for a classic damped harmonic oscillator (Bohren & Huffman 1983); γ and x_0 are respectively the FWHM and peak position of the Drude profile;² c_4 determines the far-UV curvature term represented by $F(x)$. The resulting analytical fits are plotted in Figures 2 and 3; and the fitted parameters c_1 , c_2 , c_3 , c_4 , and γ are tabulated in Table 3.

To quantify the dust properties, we fit both extinction types in terms of the silicate-graphite dust model. The model fits and parameters are respectively shown in Figures 2,3 and in Table 4. The model for the flat “Type-I” extinction curve is dominated by *large* silicate grains (with $f_{\text{gra}} \approx 0$ and a flat size distribution). In contrast, the model for the steep “Type-II” extinction has a much steeper size distribution, indicating the richness of *small* dust in the host galaxies with a “Type-II” extinction curve.

5. Discussion

Previous efforts in deriving the dust extinction of GRB host galaxies all assume an initial power-law for the GRB intrinsic spectrum (as expected from the standard fireball model), and an extinction curve of known types such as that of MW, SMC, LMC, the Calzetti et al. (1994) law suitable for local starburst galaxies, and the Maiolino et al. (2001) law suggested

²In the Galactic ISM, the strength and width of the 2175 Å extinction bump vary with environment while its peak position is quite invariant (see Li 2005). We therefore fix x_0 at $4.6 \mu\text{m}^{-1}$.

for the dust in the circumnuclear region of AGNs (e.g. see Stratta et al. 2004 and Kann et al. 2006 for recent examples). Our approach, without the need for an initial assumption of specified extinction types, is more favourable because of the lack of a priori knowledge of the extinction in the GRB hosts. The fact that neither of the two extinction types derived in this work resembles that of MW, SMC and LMC (see Figs. 2,3) challenges the initial assumption of specific extinction types.

In consistent with previous studies, this work also finds no evidence for the 2175 Å extinction bump.³ The carrier of this bump remains unidentified over 40 years after its first detection. It is generally believed to be caused by aromatic carbonaceous (graphitic) materials, likely a cosmic mixture of polycyclic aromatic hydrocarbon (PAH) molecules (see Li 2005 and references therein). The nondetection of the 2175 Å extinction bump in the GRB hosts could be explained in terms of (1) the depletion of its carrier (e.g. PAHs) by condensation onto the ice mantles coated on the dust in the dense star-forming regions in which GRBs are embedded, and (2) the destruction of its carrier by UV/X-ray radiation in the immediate vicinities (up to ~ 20 pc) of bursts.

Our Type-I extinction curve (see Fig. 2) is more gray (i.e. with a much weaker dependence on wavelength) than that of MW, SMC, and LMC. Gray dust has been invoked by a number of authors (e.g. Savaglio et al. 2003, Savaglio & Fall 2004; Stratta et al. 2004, 2005) to account for the small ratios of extinction and/or reddening (derived from fitting the afterglow SEDs) to H column densities (determined from X-ray or Ly α absorption) of GRB hosts, which are usually smaller than that of MW by a factor of ~ 10 –100 (Galama & Wijers 2001, Šimon et al. 2001, Hjorth et al. 2003, Vreeswijk et al. 2004).⁴ Gray dust could be created by (1) the preferential destruction of small grains by the intense UV and X-ray radiation from the GRB (Waxman & Draine 2000, Fruchter et al. 2001, Perna et al. 2003) in the immediate GRB environment, say, within ~ 10 –20 pc around the burster (Hjorth et al. 2003, Savaglio et al. 2003, Stratta et al. 2005), and (2) the growth of dust through coagulation (which also leads to the depletion of small grains) in the high-density environments such

³The only exception is GRB 991216. Its afterglow spectrum shows a depression in flux in between 4000 Å and 5500 Å, suggesting the presence of a *red* 2175 Å-type extinction bump (at ~ 2360 Å) in the host of GRB 991216 (Vreeswijk et al. 2006). Similar red 2175 Å bumps have been previously seen in a few UV-strong, hydrogen-poor stars in the MW galaxy (see Li 2005 and references therein).

⁴Alternatively, these results can be explained by an intrinsically low dust content – a low metallicity and/or a low level of depletion of the dust-forming heavy elements in the burst environment (Fynbo et al. 2003, Hjorth et al. 2003, Vreeswijk et al. 2004, Fruchter et al. 2006). However, Savaglio et al. (2003) found that in the host galaxies of 3 GRBs both the column densities of metals (as indicated by Zn) and the depletion of heavy elements (such as Fe, Si and Cr) are large, indicating a large dust content.

as the cores of star-forming regions harboring GRB events (Maiolino et al. 2001, Stratta et al. 2004). Both mechanisms naturally lead to a dust size distribution skewed toward large grains, producing an extinction curve weakly dependent on wavelength.

Nongray extinction has also been reported (e.g. for the host of GRB 010222 by Galama et al. 2003). Our nongray, Type-II extinction curve (see Fig. 3) shows a steep increase with λ^{-1} , indicating that small grains are more abundant in the GRB host galaxies with a Type-II extinction than in those with a Type-I extinction. This is probably caused by a less complete destruction of small grains (e.g. associated with less energetic bursts of less intense UV/X-ray radiation), and/or a slower coagulation growth of dust (e.g. associated with less dense environments or metal-poorer galaxies). Since our sample is small, we do not want to overinterpret its implications. A more systematic investigation of the extinction and dust properties of a large sample of GRB host galaxies is in progress.

Finally, if one really wants to make a priori assumption of the extinction spectral shape when deriving the GRB host galaxy dust extinction, we suggest the adoption of the Fitzpatrick & Massa (1990) formulae instead of that of MW, SMC or LMC. By first visually inspecting the GRB spectrum, one can set $c_3 = 0$ (in eq.[1]) if there is no sign of the 2175 Å extinction bump or curvature on large wavelength intervals.

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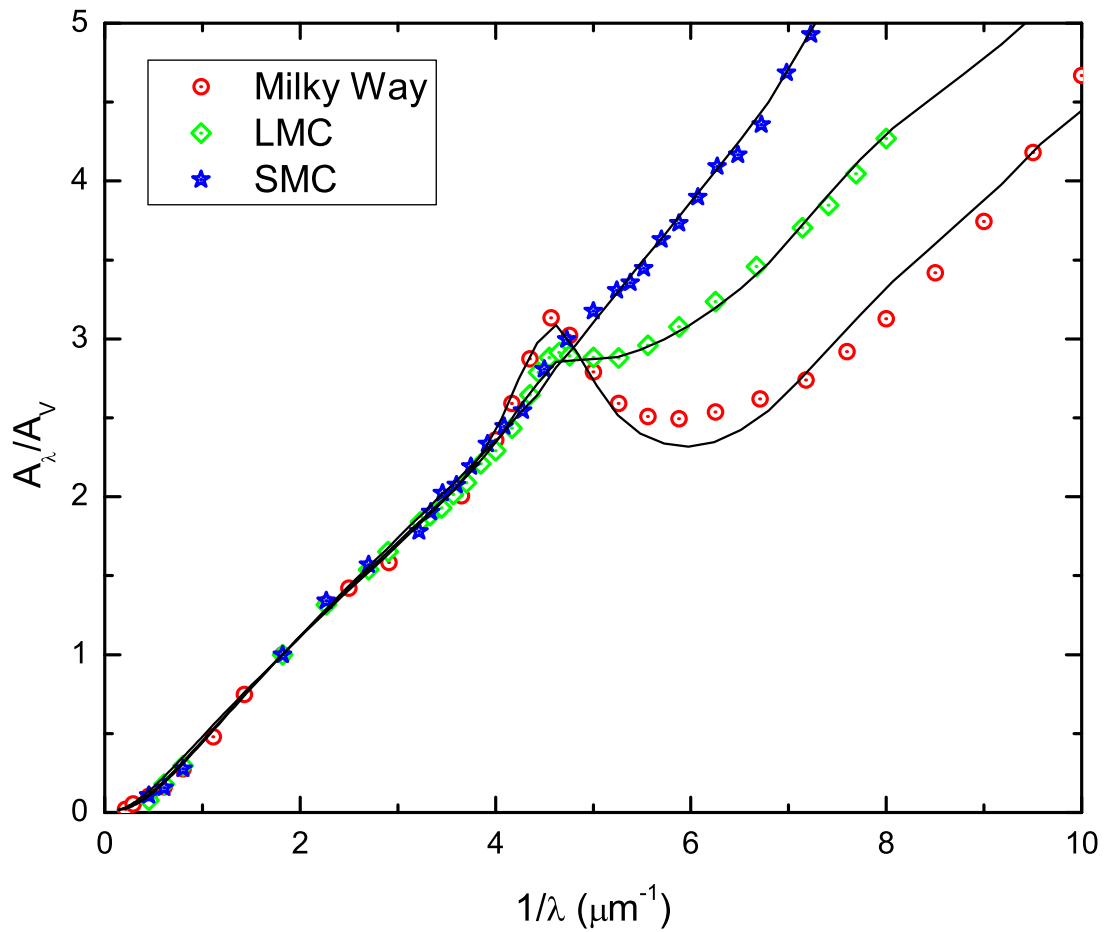


Fig. 1.— Fitting the extinction curves of the Milky Way galaxy, the SMC and LMC by the silicate-graphite model with a simple dust size distribution $dn/da \propto a^{-\eta} \exp(-a/a_c)$. Points – observational data; solid lines – model fits.

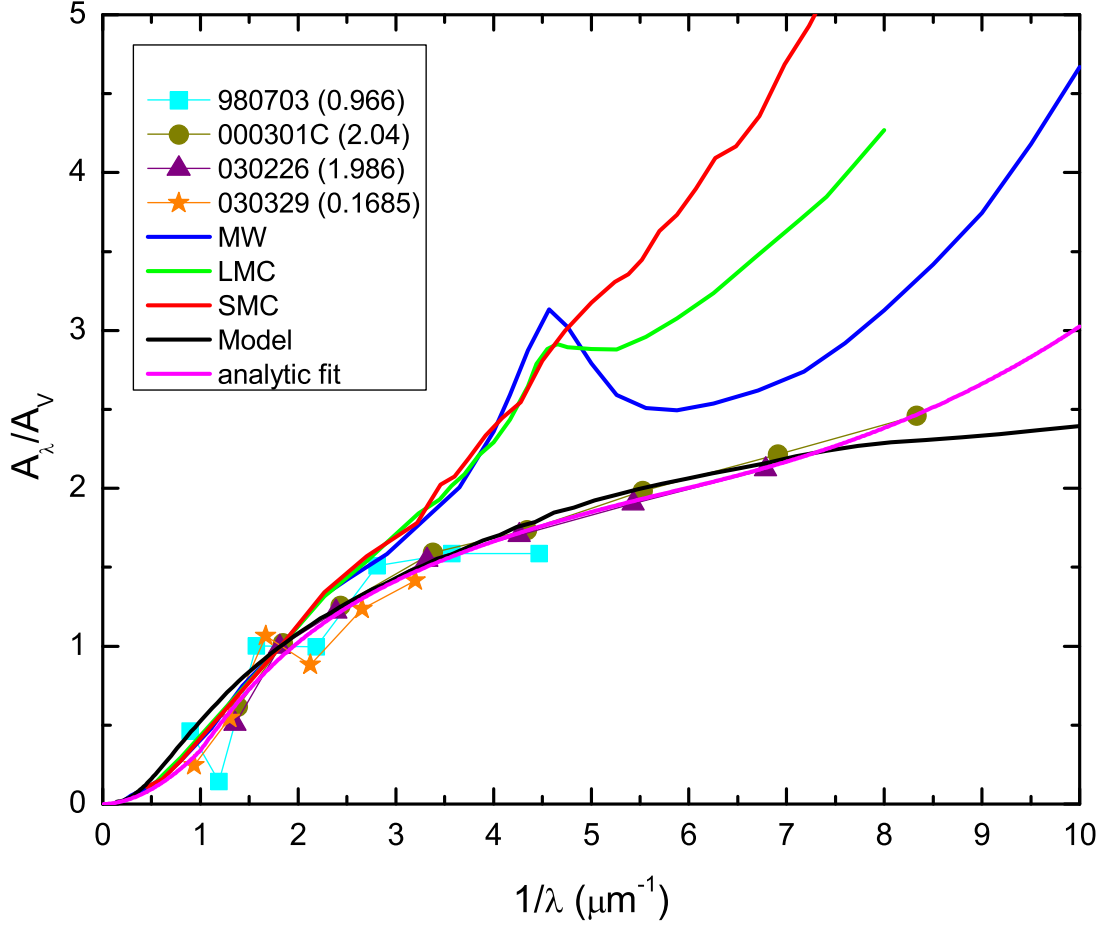


Fig. 2.— Flat, “Type-I” extinction curves (normalized to the V band) for 4 GRB host galaxies. Both axes are in the rest-frame of the GRB host. Also plotted are the model (black) and analytical (magenta) fits to the observed extinction curves. The MW, SMC and LMC extinction curves are also shown for comparison.

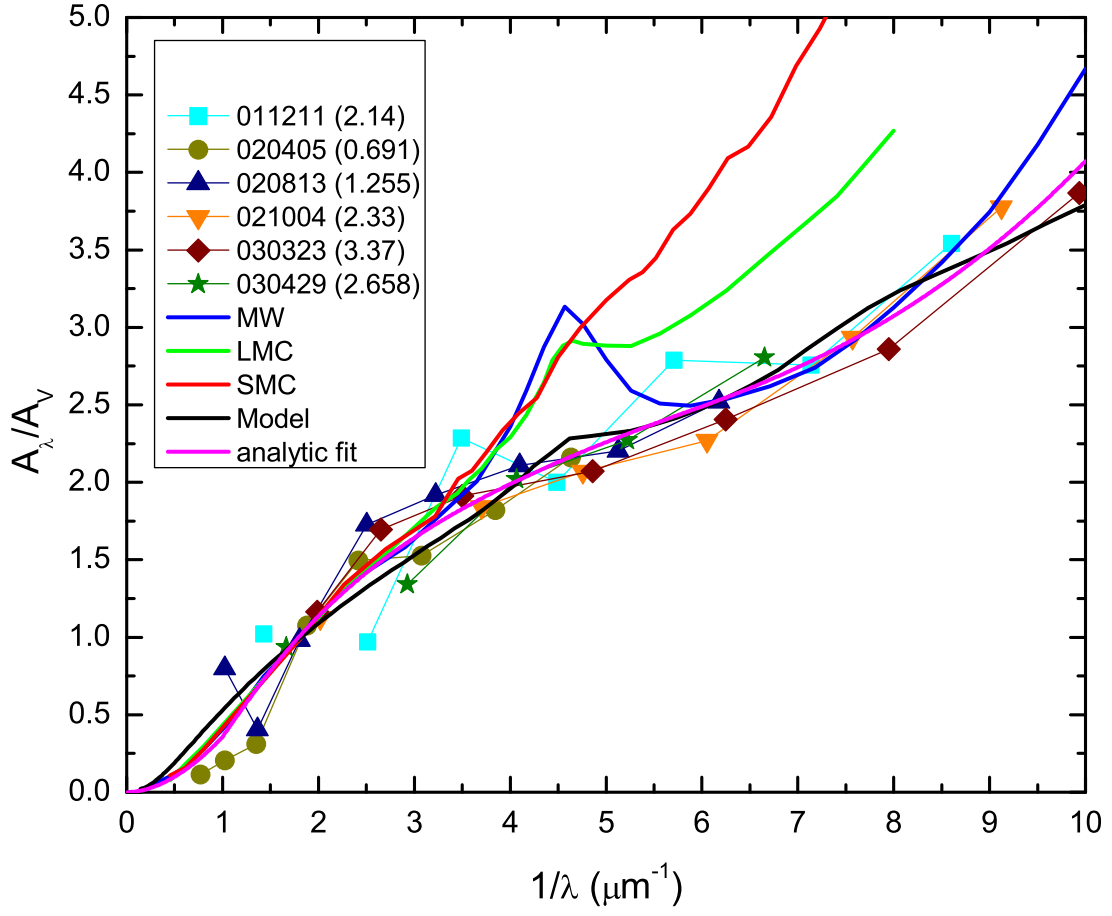


Fig. 3.— Same as Figure 2 but for the relatively steep, “Type-II” extinction curves derived for 6 GRB host galaxies.

Table 1: Optical to near-IR fluxes of 10 GRB afterglows

GRB	z	β_0	A_V^{MW} (mag)	F_ν (μJy)								t (days)	References
				U	B	V	R	I	J	H	K		
980703	0.966	1.07	0.192	...	2.7	3.4	4.6	7.6	10.8	21.8	25.5	5	1
000301C	2.0404	0.56	0.308	11.6	14.1	17.3	21.6	26.1	35.3	44.9	60.6	3.1	2
011211	2.14	0.63	0.142	11.4	13.5	15.5	19.1	21.9	29.5	...	42.0	0.57	3
020405	0.691	0.5	0.180	5.4	7.2	9.5	10.9	15.7	28.6	34.9	42.5	1.98	4
020813	1.255	0.52	0.370	6.1	7.7	9.0	11.1	13.7	22.4	33.2	32.5	1.93	5
021004	2.33	0.45	0.198	4.3	7.2	11.1	13.7	17.2	...	32.6	...	5.5	6
030226	1.986	0.33	0.062	...	17.3	20.4	23.9	27.6	35.1	42.1	56.2	0.8	7
030323	3.3718	0.28	0.163	...	2.0	5.2	7.6	10.8	16.5	21.0	37.7	2.4	8
030329	0.1685	0.48	0.083	1200	1400	1770	1860	2530	3300	...	...	0.7	9
030429	2.658	0.63	0.204	...	...	11.2	16.3	21.1	34.3	...	57.8	0.548	10

Note. — Data are all taken from the cited references. The Galactic visual extinction A_V^{MW} is derived from the reddening maps of Schlegel et al. (1998). The UBVRIJHK fluxes are measured in the observer frame; z is the redshift of the burst; t is the time when the data was taken since the burst; and β_0 is the intrinsic spectral index derived from the standard afterglow model (see §2).

References. — (1) Frail et al. 2003; (2) Jensen et al. 2001; (3) Jakobsson et al. 2003; (4) Stratta et al. 2005; (5) Covino et al. 2003; (6) Holland et al. 2003; (7) Klose et al. 2004; (8) Vreeswijk et al. 2004; (9) Bloom et al. 2004; (10) Jakobsson et al. 2004.

Table 2: Extinction in the rest frame of each burst calculated from Table 1. A_V is obtained by extrapolating an analytical fit of $A_\lambda - A_{[V(1+z)]}$ to $\lambda \rightarrow \infty$ (see §2).

GRB	z	β_0	A_V	$A_\lambda - A_{[V(1+z)]}$							
				U	B	V	R	I	J	H	K
980703	0.966	1.07	0.48	...	0.29	0.29	0.24	0	0	-0.41	-0.26
000301C	2.0404	0.56	0.35	0.51	0.43	0.34	0.26	0.21	0.1	0.01	-0.13
011211	2.14	0.63	0.07	0.18	0.12	0.13	0.07	0.09	-0.002	...	0.002
020405	0.691	0.5	0.57	0.66	0.47	0.30	0.28	0.04	-0.39	-0.45	-0.51
020813	1.255	0.52	0.43	0.65	0.52	0.48	0.39	0.31	-0.01	-0.26	-0.09
021004	2.33	0.45	0.51	1.42	0.99	0.65	0.55	0.43	...	0.06	...
030226	1.986	0.33	0.40	...	0.45	0.36	0.28	0.22	0.09	-0.002	-0.20
030323	3.3718	0.28	0.92	...	2.64	1.71	1.29	0.99	0.84	0.64	0.15
030329	0.1685	0.5	0.36	0.14	0.08	-0.05	0.03	-0.16	-0.26	...	...
030429	2.658	0.63	0.41	...	...	0.74	0.52	0.42	0.14	...	-0.03

Table 3: Parameters for fitting the extinction curves of GRB host galaxies with the Fitzpatrick & Massa (1990) formulae. Note that x_0 is fixed at $4.6 \mu\text{m}^{-1}$ and is not a free parameter (see Eq.[1]).

	c_1	c_2	c_3	c_4	$\gamma \ (\mu\text{m}^{-1})$	k
Type-I	-0.342	0.181	331.86	0.040	16.040	0.340
Type-II	-0.343	0.263	268.34	0.061	14.431	0.358

Table 4: Parameters for modeling the 2-type extinction curves of GRB host galaxies (as well as that of MW, SMC and LMC) with the silicate-graphite dust model.

Galaxy	η	a_c (μm)	f_{gra}	$\chi^2/\text{dof}^{\text{a}}$
MW	3.14	0.17	0.70	0.30
LMC	3.16	0.20	0.29	0.04
SMC	3.33	0.26	0.02	0.06
Type-I	2.61	0.21	0	0.63
Type-II	3.09	0.29	0.22	1.97

^a $\chi^2 \equiv \sum_{\text{all } \lambda} \sum_{\text{all GRBs}} [(A_{\lambda}/A_V)_{\text{mod}} - (A_{\lambda}/A_V)_{\text{obs}}]^2 / \sigma^2$ is obtained by summing up all wavebands and all GRBs, where σ is the uncertainty for a given GRB at a given band.